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Temporal Patterns in Catch Rates of Juvenile Chinook Salmon and Trawl Net Efficiencies in the Lower Sacramento River

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Introduction

A full understanding of spatial and temporal patterns in distribution and abundance of a species is vital to making well informed decisions regarding management of the species (Walters 1991, Gerber et al. 1999, Forney 2000). U.S. Fish and Wildlife Service (USFWS) has monitored populations of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, throughout the San Francisco Bay Delta Estuary (hereafter, “Delta”) since the early 1970’s. A primary purpose of the monitoring program is to provide managers of Delta water operations with information on patterns in distribution and abundance of migrating juvenile Chinook salmon that allows them to make informed decisions about water operations. Until now, efforts to determine salmon abundance have been conducted primarily during morning to mid-day hours with few exceptions (see San Joaquin River Group Authority 2005). However, there is growing evidence that juvenile salmonids in other regions exhibit complex diel patterns in activity levels (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Reebs 2002, Johnston et al. 2004). These studies have found that salmon are primarily diurnal during spring and summer months but primarily nocturnal during fall and winter months. Given these complex temporal patterns in activity level of salmonids, it is important to determine whether juvenile Chinook salmon exhibit similar diel activity patterns in areas sampled by the USFWS. The existence of such patterns may have implications for the accuracy of our estimates of salmon abundance at different times of year.

Sampling techniques used to gain information on patterns in distribution and abundance of an organism often do not fully account for all individuals in a given area, leading to less accurate abundance estimates. For example, a lack of fish catch by a given sampling gear does not necessarily signify that the fish is not present. The fish may indeed be present, but the net is not efficient in successfully capturing the individual. The fish may be just outside the sampling area or be able to avoid or pass through the sampling gear. One approach to partition these two potential explanations for lack of catch -- fish presence versus sampling efficiency -- is to observe fish behavior *in situ* via radio telemetry (Hiscock et al. 2002, Pollock et al. 2004), hydroacoustics (United States Bureau of Reclamation 2004), or snorkel surveys. When these techniques are impractical, one may calculate efficiency of the sampling technique by estimating the proportion of fish that are caught from a known number of fish. This efficiency rate provides a correction factor for future catches (Wickwire and Stevens 1966).

The purpose of this study was to evaluate the accuracy of sampling procedures conducted by the USFWS to ensure that we are providing the best information possible to water operators for management decisions. By timing our sampling with scheduled hatchery releases of tagged juvenile Chinook salmon, we addressed two goals: (1) to examine whether diel patterns in catch per unit effort

(CPUE) differed between spring and late fall sampling periods, and (2) to determine catch efficiencies of midwater and Kodiak trawl nets on the Sacramento River. To address the first goal, we sampled continually for ~24 hours after hatchery releases in spring and late fall to recover released individuals. In addition, we collected data on juvenile Chinook salmon from outside of the release to compare diel patterns in CPUE of released salmon to those of non-released salmon. To address the second goal, we calculated the proportion of released salmon available for capture that were caught in midwater and Kodiak trawl nets.

Methods

Study site

Sampling was conducted along a 3.2 km stretch of the Sacramento River near Sherwood Harbor (River Mile [RM] 55). River width through this stretch ranges from 142-182 m. Tides in the area are semi-diurnal.

Sampling

Fish were captured in spring using a midwater trawl net and in late fall using a Kodiak trawl net. Twenty minute trawls were conducted on a near continuous basis during six periods, three in spring (05/15/03-05/16/03, 04/15/05-04/16/05, and 04/29/05-04/30/05) and three in late fall (12/03/02-12/04/02, 12/05/03-12/06/03, and 12/06/04-12/07/04). All trawls were conducted in the center of the river in an upstream direction. Water temperature was recorded at the beginning of all trawls whereas water turbidity was measured using a Secchi disk at the beginning of daytime trawls only. River flow data for the Sacramento River at Freeport was obtained from the California Department of Water Resources data exchange (California Department of Water Resources 2005).

Trawling was timed in coordination with hatchery releases of coded wire tagged (CWT) juvenile Chinook salmon at the Broderick boat ramp in West Sacramento, 7.25 km upstream of the sampling area. Sampling began near the time of each release and continued for approximately 24 hours. CWT fish released in spring were all fall-run Chinook salmon from the Feather River Hatchery (Table 1). Fish released in late fall were late fall-run Chinook salmon from Coleman National Fish Hatchery. Fish were not released in relation to a specific tidal stage.

Table 1 Hatchery release information for coded wire tagged Chinook salmon associated with the current study.

Release date	*Release time*	*# of fish released*	*Sampling period*
Late fall			
12/3/02	1420	69,490	12/3/02, 2036 to 12/4/02, 1352
12/5/03	1215	30,738	12/5/03, 1248 to 12/6/03, 1356
	1515	33,809	
12/6/04	1115	25,279	12/6/04, 1138 to 12/7/04, 0746
	1625	25,482	
Spring			
5/15/03	1045	50,284	5/15/03,1155 to 5/16/03, 1158
4/15/05	1234	51,144	4/15/05,1234 to 4/16/05, 1154
4/29/05	1210	51,390	4/29/05,1241 to 4/30/05, 1203

A midwater trawl net was used during spring sampling. The net fishes the top 1.8 m of the water column and is 4.6 m wide. The net is composed of six panels, each decreasing in mesh size (0.32-20.32 cm, USFWS 2003) towards a cod end. When deployed, two metal bottom depressors sink and spread the net at the bottom lead line while a second pair of metal hydrofoils, attached to floats, spread the top of the net at the surface. The net is fished 30.5 m behind the boat.

A larger Kodiak trawl net was used during late fall sampling. The net fishes the top 1.8 m of the water column and is 7.5 m wide when fully extended. A 1.8 m bar attached to the front of each wing keeps the lead line at a constant depth. The net is made of variable mesh and is composed of four panels, each decreasing in mesh size (0.32-2.54 cm) towards a cod end. The cod end is capped with an aluminum live box (33 X 33 X 26 cm) with baffles that protect enclosed fish from flow pressure to minimize fish mortality. The net is fished 30.5 m behind two boats.

After each trawl, all Chinook salmon were counted to race, while all other fish were counted to species. Race of all CWT salmon was determined from release information provided by hatcheries. Race of untagged salmon was determined using length-at-date criteria (Greene 1992). We also measured the fork lengths of =50 salmon from each race and =30 individuals from each other species. Diel patterns are reported here for Chinook salmon only. For our analysis, salmon were categorized as (1) targeted, which were individuals from the associated hatchery release, or (2) non-targeted, which were all other salmon, including those from other CWT releases not associated with our study. All salmon with a clipped adipose fin were returned to the laboratory and examined for presence of a CWT. If present, the CWT was extracted and the tag code was read and recorded. All other fish caught were released.

Catch per unit effort (in fish/m^3) of each trawl was calculated as:

$$CPUE = \frac{catch\ per\ tow}{volume\ through\ net} \quad (1)$$

Trawl nets do not always open completely while under tow, causing net mouth area to vary within and among tows. This issue has been addressed previously by calculating mean net mouth area for each net type (Midwater trawl = 5.08 m^2, Kodiak trawl = 12.54 m^2; USFWS 2003), which we used in our calculations. Volume during each trawl was calculated by converting rotations of a General Oceanics mechanical flow meter (model #2030) attached to the boat using the net mouth area and standard equations. All CPUE calculations were multiplied by 10,000 for ease of presentation.

Net Efficiency

We calculated net efficiency for each release, $NE_{release}$, as:

$$NE_{release} = \frac{N_{recovered}}{N_{available}} \quad (2)$$

where $N_{recovered}$ = number of salmon captured in the trawl net, $N_{available}$ = number of salmon available for capture. Because we sampled during only a portion of time of the entire sampling period, p_{time}, and on only a portion of the width of the river, p_{width}, not all fish released were available for capture by nets. Therefore, we corrected the number of fish from the release to gain a more accurate estimate of $N_{available}$, which was calculated as:

$$N_{available} = N_{release} \times p_{time} \times p_{width} \quad (3)$$

where $N_{release}$ = number of salmon released upstream. p_{time} was calculated as:

$$p_{time} = \frac{t_{sampled}}{t_{total}} \quad (4)$$

where $t_{sampled}$ = amount of time sampled (when net was in the water), and t_{total} = total time during which trawls were conducted ($t_{sampled}$ and time when net was out of the water). p_{width} was calculated as:

$$p_{width} = \frac{w_{net}}{w_{channel}} \quad (5)$$

where w_{net} = width of trawl net, and $w_{channel}$ = average channel width in sampling area.

These calculations were based on several assumptions: (1) all released salmon moved downstream from the release site to the sample site; (2) channel depth is uniform across the width of the channel; and (3) fish were uniformly distributed through time and space during sampling. Although it is probable that none of these assumptions were met completely, this calculation provides the best estimate of net efficiency currently available.

All trawls were categorized as occurring in one of three times periods: diurnal, nocturnal, and crepuscular, which we define here as the periods between first daylight and sunrise and between sunset and last daylight. These times were taken from Tidelog for Northern California (1996-2005). When a trawl was conducted during two time periods, it was categorized as the period during which the majority of time was spent. If a trawl was conducted during two time periods equally, it was categorized as the first time period.

Data Analysis

We conducted nested analyses of variance (ANOVAs) to determine whether temperature or flow rates varied among time period, among sample dates, or between seasons. In the analyses, sample date was nested within season and time period was nested within sample date within season. Because turbidity was measured during diurnal hours only, we could not determine whether it varied among time periods. Instead, we conducted a nested ANOVA to determine whether turbidity varied between seasons or among dates nested within seasons.

For CPUE, separate analyses were conducted for targeted and non-targeted salmon. Because data severely violated the assumption of normality (Shapiro-Wilkes test; $p < 0.001$), a nonparametric analysis was required. We analyzed CPUE data separately by season because dates were nested within season, and to our knowledge, a nonparametric nested ANOVA with a block design and unequal replication among cells within blocks does not exist. Therefore, for each season separately, we conducted a non-parametric ANOVA using the Mack-Skillings (Mack and Skillings 1980; Skillings and Mack 1981) procedure to determine whether there were differences in CPUE among times of day. This procedure allows unequal replication among cells within blocks (in our study, cells = time period and blocks = dates) and the resulting test statistic, the MS-statistic, can be compared to a two-way distribution.

To determine whether flow rate influenced the speed at which released fish travel down stream and, hence, the timing of their capture, we conducted two linear regressions: flow rate versus time between fish release and first catch, and flow rate versus time between fish release and peak CPUE.

To determine whether there were differences in fork length of targeted or non-targeted salmon among seasons, sample dates, and time period, we conducted parametric nested ANOVAs where date was nested within season and time period was nested within date nested within season. Assumptions of normality and homoscedasticity were not critically violated.

All parametric statistical analyses were conducted in SYSTAT 11 or JMP 5.1. The Mack-Skillings nonparametric analyses for CPUE data were conducted by hand.

Results

Physical Variables

Water temperature was significantly higher during spring sampling periods (16.6 ± 0.9° C) than during late fall sampling periods (10.7 ± 0.2° C; MS = 990.90, $F_{1,243}$ = 19651, $P < 0.0001$; Figure 1A). Temperatures varied significantly among dates within season (MS = 90.07, $F_{4,243}$ = 1786, $P < 0.0001$) and among time periods within date within season (MS = 0.24, $F_{12,243}$ = 4.729, $P < 0.0001$). Temperatures during the day were ~1° C higher than those during crepuscular and night periods.

Flow rates were significantly higher during spring sampling (24596 ± 1024 cfs) than during late fall sampling (12388 ± 554 cfs; MS = 3.28×10^9, $F_{1,125}$ = 450.149, $p < 0.0001$; Figure 1B). Flow rates also varied significantly among sample dates within season (MS = 7.23×10^8, $F_{4,125}$ = 99.317, $p < 0.0001$) and among time period within sample dates within season (MS = 2.82×10^7, $F_{4,125}$ = 3.873, $p < 0.0001$). Daytime flows were ~1300 cfs higher than crepuscular and night time flows.

Turbidity levels were significantly higher (i.e., Secchi readings were lower) during spring sampling periods (Secchi: 0.75 ± 0.02 m) than during late fall sampling periods (Secchi: 0.99 ± 0.03 m; MS = 2.22, $F_{1,136}$ = 894.2, $p < 0.0001$; Figure 1C). Turbidity also varied significantly among sample dates within season (MS = 1.52, $F_{4,136}$ = 611.9, $p < 0.0001$) and among time periods within sample dates within season. Turbidity and flow rates were positively correlated ($r = 0.87$, $n = 6$, $p = 0.03$).

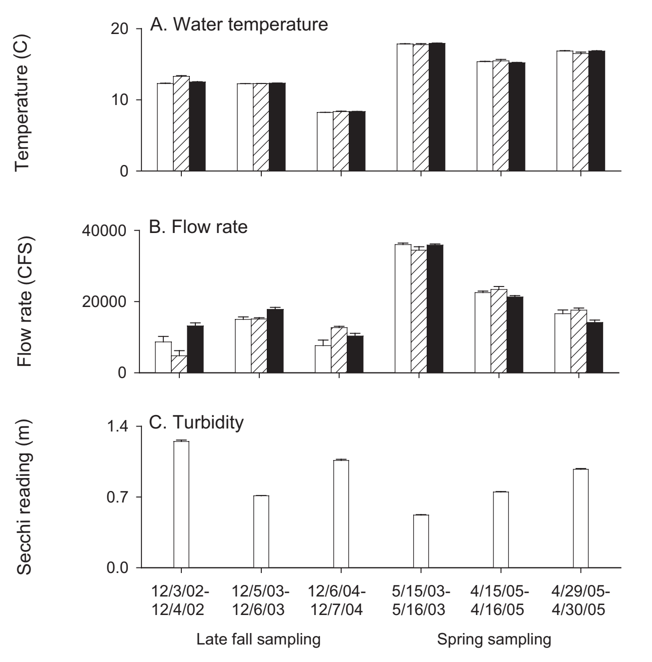

Figure 1 Summary of (A) temperature, (B) flow rates, and (C) turbidity during each sampling period. A higher secchi reading corresponds to lower turbidity. Turbidity readings were conducted during daylight hours only.

Catch Per Unit Effort

There were 1312 fish from 16 species captured in 286 tows and 95.23 hours of sampling (Table 2). A total of 557 fish were caught in late fall sampling periods and 755 fish were caught in spring sampling periods. Chinook salmon were most abundant, accounting for 73.4% of all captured fish. Of the 963 Chinook salmon captured, 598 (62.1%) were targeted. Of both targeted and non-targeted salmon, late fall-run was the most abundant race captured in late fall, although one winter-run was also caught. Fall-run salmon were the most abundant race captured in spring, although 11 spring-run and one late fall-run fish were also caught. Besides Chinook salmon, only threadfin shad and inland silversides represented >1% of total fish counts.

Table 2 Total catches by species during each sampling period. Percentage of total catch within a sampling period is indicated in parentheses.

	Late fall			*Spring*			
Species	*12/3/02-12/4/02*	*12/5/03-12/6/03*	*12/6/04-12/7/04*	*5/15/03-5/16/03*	*4/15/05-4/16/05*	*4/29/05-4/30/05*	Total
Chinook salmon, *O. tshawytscha* (targeted)	130 (78.8)	31 (38.3)	53 (17.0)	188 (46.2)	175 (62.3)	21 (31.3)	598 (45.6)
Chinook salmon, *O. tshawytscha* (non-targeted)	0	3 (3.7)	1 (0.3)	217 (53.3)	102 (36.3)	42 (62.7)	365 (27.8)
Threadfin shad, *Dorosoma* petenense	28 (17.0)	35 (43.2)	238 (76.5)	0	1 (0.4)	0	302 (23.0)
Inland silverside, *Menidia beryllina*	2 (1.2)	2 (2.5)	12 (3.9)	0	0	0	16 (1.2)
Rainbow trout/Steelhead, O. mykiss	0	0	1 (0.3)	0	2 (0.7)	2 (3.0)	5 (0.4)
American shad, *Alosa sapidissima*	2 (1.2)	0	0	1 (0.3)	1 (0.4)	0	4 (0.3)
Channel catfish, *Ictalurus* punctatus	1 (0.6)	2 (2.5)	0	0	0	1 (1.5)	4 (0.3)
River lamprey, *Lampetra ayresii*	2 (1.2)	0	2 (0.6)	0	0	0	4 (0.3)
Yellowfin goby, *Acanthogobius flavimanus*	0	0	3 (1.0)	0	0	0	3 (0.2)
Bluegill, *Lepomis macrochirus*	0	1 (1.2)	1 0.3)	0	0	0	2 (0.2)
Common carp, *Cyprinus carpio*	0	2 (2.5)	0	0	0	0	2 (0.2)
Wakasagi, *Hypomesus* nipponensis	0	2 (2.5)	0	0	0	0	2 (0.2)
Black crappie, *Pomoxis* nigromaculatus	0	1 (1.2)	0	0	0	0	1 (0.1)
Fathead minnow, *Pimephales promelas*	0	1 (1.2)	0	0	0	0	1 (0.1)
Golden shiner, *Notemigonus* crysoleucas	0	0	0	0	0	1 (1.5)	1 (0.1)
Striped bass, *Morone saxatilis*	0	0	0	1 (0.3)	0	0	1 (0.1)
White crappie, P. annularis	0	1 (1.2)0	0 0	0	0	0	1 (0.1)
Total	165	81	311	407	281	67	1312

We excluded the first 12 trawls on 12/3/02 (between 1358 and 1857h) because the net was fished incorrectly. Despite this, there were clear diel patterns in mean CPUE of targeted salmon, and these patterns switched between seasons (Figure 2). In late fall, CPUE was significantly greater at night than during diurnal and crepuscular hours (MS-statistic = 9.1; $p < 0.001$). We caught 95.3% of all targeted salmon at night, 1.4% during the day, and 3.3%

during crepuscular periods. In spring, CPUE was highest during the day and lowest at night (MS-statistic = 189.4; $p < 0.001$). We caught 94.6% of all targeted salmon in spring during the day, 2.1% during crepuscular periods, and 3.4% at night.

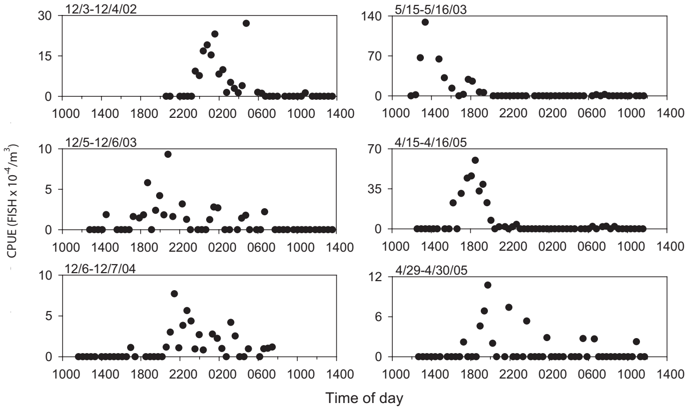

Figure 2 Catch per unit effort (CPUE) of targeted juvenile Chinook salmon from hatchery releases. Clear regions = day; striped regions = crepuscular hours; cross-hatched = night. Arrows indicate release times. Note change in scale among panels. The first 12 trawls on 12/3/02 (between 1358 and 1857h) were excluded because the net was fished incorrectly.

Non-targeted salmon comprised 27.8% of all fish caught in trawls (Table 2). Only four salmon were captured during the three late fall sampling periods combined, precluding formal statistical analysis (Figure 3). Two of these fish were caught at night and two were caught during the day. Therefore, no clear diel patterns in CPUE of non-targeted salmon during late fall could be detected. In spring, CPUE was greater during the day and lowest at night (MS-statistic = 200.7, $p < 0.001$). We caught 84.3% of all non-targeted salmon in the spring during the day, 7.0% during crepuscular periods, and 2.3% at night. This pattern is similar to CPUE of targeted fish in spring, but the reverse pattern of CPUE of targeted fish in late fall.

The relationship between flow rate and time between the release and first catch of targeted fish is not statistically significant, although the trend indicates that higher flow rates reduce the time between the release and first catch ($R^2 = 0.60$; $p = 0.13$; Figure 4). There was a highly significant negative relationship between flow rate and time until peak CPUE ($R^2 = 0.97$; $p = 0.002$).

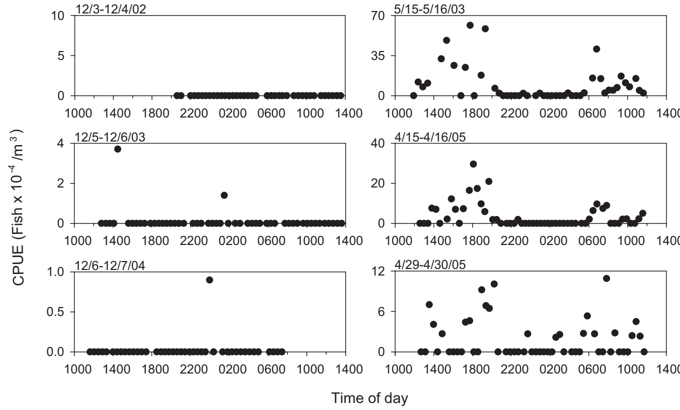

Figure 3 Catch per unit effort (CPUE) of non-targeted juvenile Chinook salmon (i.e., untagged salmon and tagged salmon from an unassociated release). Clear regions = day; striped regions = crepuscular hours; cross-hatched = night. Note change in scale among panels. The first 12 trawls on 12/3/02 (between 1358 and 1857h) were excluded because the net was fished incorrectly.

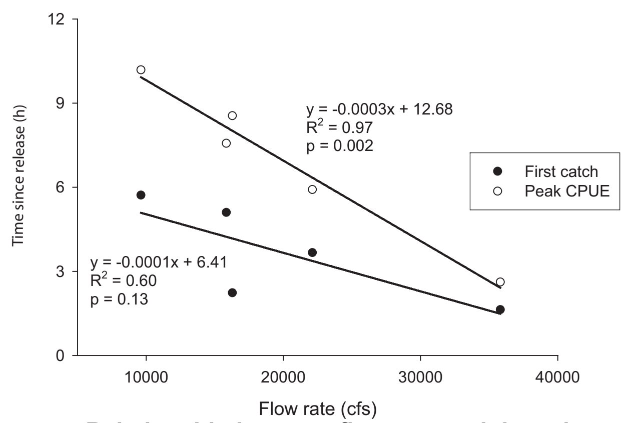

Figure 4 Relationship between flow rate and time since fish release until first catch (darkened circles), and time since fish release until peak CPUE (open circles).

Fork lengths

Mean fork length of targeted salmon was larger during late fall sampling (121.70 ± 1.19 mm) than during spring sampling (80.24 ± 0.57 mm; MS = 19236.97, $F_{1,595} = 128.1$, $p < 0.0001$; Figure 5A). Mean fork lengths differed among days within season (MS = 1209.06, $F_{4,595} = 8.1$, $p < 0.0001$) and among time periods nested within day nested within season (MS = 694.32, $F_{10,595} = 4.6$, $p < 0.0001$), although there were no clear patterns among time periods or dates within seasons.

Mean fork length of non-targeted salmon varied by season (MS = 2961.86, $F_{1,342} = 52.70$, $p < 0.0001$, Figure

5B). Mean fork length was 113.0 ± 15.7 mm in late fall and 76.7 ± 0.5 mm during spring sampling. Mean fork lengths also varied among sample date within season (MS = 650.47, $F_{3,342}$ = 11.57, p < 0.0001) and among time period nested within sample date within season (MS = 534.91, $F_{7,342}$ = 9.52, p < 0.0001), although, as with targeted salmon, there were no consistent patterns among time periods or dates within season.

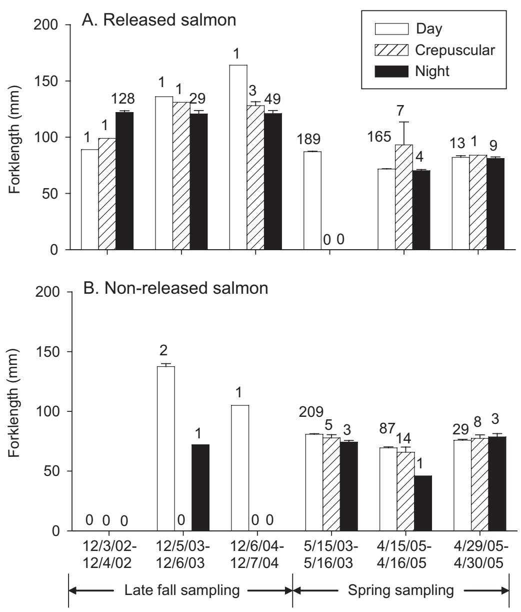

Figure 5 Mean fork length (±1 SE) of (A) targeted and (B) non-targted juvenile Chinook salmon caught in trawls during sampling. Numbers above bars indicate number of fish upon which means were based.

Net Efficiency

Mean efficiency of the midwater trawl net was 0.034 ± 0.007 and values ranged from 0.015-0.054 (Table 3). Mean efficiency of the Kodiak trawl net was 0.122 ± 0.031 and values ranged from 0.019-0.195. There was no statistically significant difference between gear types (t_4 = 1.628, p = 0.18), although the trend indicates that the Kodiak trawl net was much more efficient than the midwater trawl net. A power analysis indicates that the statistical power was 0.57 and that, given the variances we found, at α = 0.05, we must conduct a minimum of five sample dates from each trawl type to obtain the generally accepted statistical power of 0.80.

Table 3 Efficiency ($NE_{release}$) of midwater and Kodiak trawl nets used at Sacramento.

Midwater trawl (Late fall)		*Kodiak trawl (Spring)*	
Sample dates	*NErelease*	*Sample dates*	*NErelease*
12/3-12/4/02	0.054	5/15-5/16/03	0.195
12/5-12/6/03	0.015	4/15-4/16/05	0.151
12/6-12/7/04	0.032	4/29-4/30/05	0.019
Mean	0.034	Mean	0.122
(SE)	(0.007)	(SE)	(0.031)

Discussion

Although not statistically significant, the Kodiak trawl net was four times as efficient as the midwater trawl net during our sampling (Table 3). Noel (1980) found that Kodiak trawls are more efficient than midwater trawls, concluding that the use of two boats during Kodiak trawls will herd fish into the net, increasing net efficiency. Further, the largest mesh size of the midwater trawl net (20.32 cm) used in spring is eight times greater than that of the Kodiak trawl net (2.54 cm) used in late fall. This larger mesh size increases the ability of fish to slip through the mesh, which would reduce the efficiency of the midwater trawl net. Also, the Kodiak trawl net is 2.6 m wider than the midwater trawl net, requiring fish to travel a longer horizontal distance if they attempt to escape from the net. These latter two explanations are confounded, however, by other differences between late fall and spring, such as fish length, turbidity, and water temperature (Figures 1, 5).

CPUE of targeted juvenile Chinook salmon in spring sampling periods was significantly greater during the day and significantly greater at night during late fall sampling periods (Figure 2). Although these patterns are consistent with those observed in other salmonid studies (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Johnston et al. 2004), it appears that they were driven primarily by flow rate and time of day of the fish release (Figure 4). Flow rate explained 60% and 97% of the variation in time since the release until first fish catch and peak CPUE, respectively. As a result, it is not reasonable to consider CPUE of targeted salmon in this study in assessing diel patterns in CPUE, regardless of their consistency with other studies. This relationship between timing of fish capture suggests that the timing of the release will influence the timing of fish capture.

CPUE of non-targeted juvenile Chinook salmon in spring sampling periods was significantly greater during the day, consistent with other studies, although low catches of non-targeted salmon in late fall (n = 4 fish) precluded formal analysis to evaluate diel patterns in CPUE with confidence (Figure 3). To properly assess diel patterns of CPUE in late fall, sampling efforts must be increased to catch a sufficient number of non-targeted salmon.

There have been six additional surveys over 24 hour periods conducted for or by USFWS since 1996 in the Delta to which we can compare to our findings (Table 4). Although we conducted no formal statistical analysis on these data, CPUE of Chinook salmon in spring surveys was generally greatest during the day and crepuscular hours and lowest at night. CPUE of Chinook salmon in fall/late-fall surveys was generally greatest during nocturnal and crepuscular hours and lowest during the day. High CPUE during crepuscular periods may be due to spillover from other time periods. In fact, in the two spring surveys where CPUE was greatest during crepuscular periods, CPUE during the day was approximately three times greater than that of night time. In the fall sampling date where CPUE was greatest during crepuscular periods, CPUE at night was nearly 69 times greater than CPUE during the day. The seasonal shift in diel patterns in these surveys is largely consistent with those in other studies (Sagar and Glova 1988, Ledgerwood et al. 1991, Fraser et al. 1993, 1995, Fraser and Metcalfe 1997, Hiscock et al. 2002, Johnston et al. 2004). Also, patterns in CPUE during spring are consistent with those of non-targeted salmon in the current study, although we were unable to compare fall patterns owing to low catches in our study.

Many factors differ between fall and spring sampling periods that may contribute to the shift in diel CPUE patterns between seasons (Table 4). First, temperature has been recognized as an important factor responsible for the shift in diel activity level by other species of salmon (Fraser et al. 1993, 1995). Fraser et al. (1993) showed that, under laboratory conditions, juvenile Atlantic salmon (*Salmo salar*) change from diurnal to nocturnal with a decrease in water temperature. A threshold temperature of ~8-12° C has been suggested previously, below which salmonids switch from diurnal to nocturnal activity patterns (Gibson 1978, Fraser et al. 1993, 1995). A plausible mechanism for the temperature-dependent shift in activity levels involves a trade-off between foraging efficiency and predation risk (Fraser et al. 1993, 1995). When temperatures decrease, the metabolism of these exothermic organisms is reduced. A lower metabolism reduces their mobility, increasing their risk of predation because they are less able to escape predation from endothermic predators (e.g., birds and aquatic mammals). A lower metabolism also reduces energy requirements of a salmon. As a result, they can "afford" to forage during nocturnal hours when foraging efficiency is reduced (reduced foraging efficiency of salmonids at night has been demonstrated by Fraser and Metcalfe 1997). In warmer conditions, fish metabolism is higher and, thus, energy requirements are higher. As a result, salmon must forage during the day when their foraging efficiency is greater, despite higher predation risk. Spring patterns in the current study are consistent with this hypothesis (Figure 1), although we cannot determine the influence of temperature in late fall because of low fish counts. However, seasonal patterns in CPUE of salmon from other DJFMP studies appear to be independent of water temperature (Table 4).

A second difference between late fall and spring that may influence seasonal patterns in CPUE is photoperiod. In the current study, there were nearly four hours of additional daylight during spring sampling periods compared to late fall sampling periods (Figure 2). In the other USFWS studies, there were between three and four hours of additional daylight during spring sampling periods compared to fall sampling periods (Table 4). Fraser et al. (1993) found no effect of photoperiod on *S. salar* activity levels, although Clarke et al. (1985) found that photoperiod influences the seasonal cycle of seawater adaptation in juvenile *S. salar*. However, we cannot reject this hypothesis because, to our knowledge, the effect of light regimes has not been empirically tested on Chinook salmon activity levels.

Table 4 Summary table of other studies associated with the USFWS conducted over a 24 h period. Mean (±1 SE) values of water temperature, daylight hours, turbidity, and CPUE were calculated across the entire sample period. Time period with the highest CPUE for each study is indicated with an asterisk (*).

							Mean CPUE (Fish X 10-4/m3)		
Study site	*Dates*	*Gear type*	*Predominant race*	*Mean water temperature (C)*	*Mean daylight hours (h)*	*Mean turbidity (m)*	*Day*	*Crepuscular*	*Night*
Georgiana Slough	4/29/96-5/2/96	Kodiak trawl	Fall	16.90 (0.12)	13:46 (0:01)	0.79 (0.01)	336.52 (32.18)	525.30* (105.31)	121.73 (19.12)
Walnut Grove	4/29/96-5/2/96	Kodiak trawl	Fall	16.76 (0.10)	13:46 (0:01)	0.80 (0.01)	157.16 (13.78)	162.75* (68.62)	53.96 (10.54)
Jersey Point[a]	4/29/97-5/15/97	Kodiak trawl	Fall	17.97 (0.13)	13:58 (0:02)	0.58 (0.01)	20.56* (12.86)	6.09 (0.97)	0.72 (0.09)
Delta Cross Channel[b]	10/29/01-11/1/01	Mid-water trawl	Late fall	18.21 (0.03)	10:39 (0:02)	1.35 (0.01)	0.04 (0.02)	1.44 (0.59)	1.54* (0.37)
Sacramento River, RM 27[b]	10/29/01-11/1/01	Mid-water trawl	Late fall	15.57 (0.02)	10:39 (0.02)	1.36 (0.01)	0.18 (0.05)	13.12* (3.80)	12.40 (1.47)
Chipps	12/11/03-12/12/03	Mid-water trawl	Late fall	11.47 (0.05)	9:36 (0:01)	0.66 (0.02)	0.19 (0.09)	0.25 (0.14)	0.71* (0.15)

a. Data collected by Hanson Environmental for DJFMP

b. From Hansen (2004)

Third, the type of trawl net may influence seasonal patterns in CPUE. A Kodiak trawl employs two boats that herd fish into the net (Noel 1980), whereas a midwater trawl uses one boat. Further, the Kodiak trawl net is larger and its mesh size is smaller than midwater trawls. Although McLain (1998) found that these differences between nets influence catch/tow, size of fish caught, and volume of water sampled, there is no plausible reason why the difference in net type would cause differences in diel patterns in CPUE. Regardless, data from other USFWS studies do not refute this hypothesis (Table 4). Until an experimental evaluation of diel patterns of CPUE is conducted for Kodiak and midwater trawls simultaneously (*sensu* McLain 1998), the hypothesis that gear type influences seasonal patterns in CPUE cannot be rejected.

Fourth, late fall-run salmon were the dominant race caught during fall sampling, whereas fall-run salmon were the dominant race caught during spring sampling (Table 4). Late fall-run juveniles are generally larger than fall-run juveniles (Figure 5) because they overwinter upstream and become smolts as yearlings. Larger fish tend to be less active, possibly because digestive rates are lower for larger fish, and, therefore, may not need to forage during the day (Brett and Groves 1979, Hiscock et al. 2002). Thus, seasonal patterns in CPUE observed in Table 4 may have been caused, at least in part, by the presence of different races of salmon at different times of year.

Fifth, variation in turbidity between seasons may influence patterns in CPUE between seasons. Net avoidance by fish should be more difficult when turbidity is higher (i.e., visibility is lower), resulting in higher CPUE during the day. However, because light levels have little influence on the reactive distance of fishes in highly turbid waters (Benfield and Minello 1996), this difficulty in net avoidance, and, thus, CPUE, should not vary significantly throughout a 24 h cycle in high turbidity conditions. In the current study, turbidity was high in spring (Figure 1C). However, CPUE of non-targeted salmon varied significantly during the day (Figure 3). Further, there were clear diel patterns in CPUE of salmon in even higher turbidity conditions at Jersey Point and Chipps (Table 4). Therefore, the hypothesis that turbidity drives seasonal patterns in CPUE is not supported by these studies.

Determining the mechanisms driving seasonal changes in diel patterns of CPUE of Chinook salmon is important 30because it would allow us to adjust timing of our sampling to obtain the best estimate of actual salmon abundance. At present, we generally sample only during morning and midday hours throughout the year, and conduct Kodiak trawls from October through March and midwater trawls from April through September at Sacramento. As a result, we may be underestimating fish abundances during periods when fish are predominantly nocturnal and overestimating fish abundances during periods when fish are predominantly diurnal. Thus, by determining the causes of diel patterns in salmon activity levels, we may be able to provide more accurate estimates of salmon abundance in the Delta. The actual cause of these patterns likely involves a combination of above hypotheses and possibly others not discussed. We recommend controlled laboratory experiments similar to Fraser et al. (1993) to evaluate these mechanisms. Despite inherent problems with altering fish behavior in an artificial setting, we could more easily partition the effects of these hypothesized factors on intra-annual shifts in diel patterns that can then be followed up with field investigations. Further, we recommend additional 24-hour sampling of non-released salmon at multiple times of year to determine how diel patterns vary intra-annually.

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Fulfilling a Paradoxical Mandate: Can the Environmental Water Account Ensure the Reliability of Freshwater Exports from the Sacramento-San Joaquin Delta and Simultaneously Protect Delta Smelt (*Hypomesus transpacificus*) from Excessive Entrainment?

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Introduction

The San Francisco Estuary (SFE) is often defined by its extremes. It is considered one of the most urbanized estuaries in the world (Conomos 1979, Nichols et al. 1986), and one of the most invaded estuaries in the United States, with hundreds of aquatic nonindigenous species established throughout the system (Cohen and Carlton 1995, Dill and Cordone 1997, Kimmerer and Orsi 1996). It is also one of the most managed estuaries, particularly in relation to freshwater inflow, water circulation, and water quality (Jassby and Powell 1994, CSWRCB 1995, Arthur et al. 1996, Kimmerer 2002). Despite this high level of disturbance, the SFE is one of the most valuable natural resources in the western United States (CALFED 2000). The SFE provides important habitat for numerous native plant and animal species, many of special concern, as well as several species with sport and commercial value (CALFED 2000). Conserving and restoring estuarine habitat and natural resources is a pressing and complex challenge for the responsible government agencies because human water needs continue to increase in concert with continuing urbanization of the watershed.